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High-Heat-Flux Cyclic Durability of Thermal and Environmental Barrier Coatings

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ABSTRACT

Advanced ceramic thermal and environmental barrier coatings will play an increasingly important role in future gas turbine engines because of their ability to protect the engine components and further raise engine temperatures. For the supersonic vehicles currently envisioned in the NASA fundamental aeronautics program, advanced gas turbine engines will be used to provide high power density thrust during the extended supersonic flight of the aircraft, while meeting stringent low emission requirements. Advanced ceramic coating systems are critical to the performance, life and durability of the hot-section components of the engine systems. In this work, the laser and burner rig based high-heat-flux testing approaches were developed to investigate the coating cyclic response and failure mechanisms under simulated supersonic long-duration cruise mission. The accelerated coating cracking and delamination mechanism under the engine high-heat-flux, and extended supersonic cruise time conditions will be addressed. A coating life prediction framework may be realized by examining the crack initiation and propagation in conjunction with environmental degradation under high-heat-flux test conditions.



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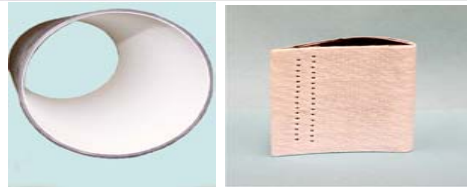
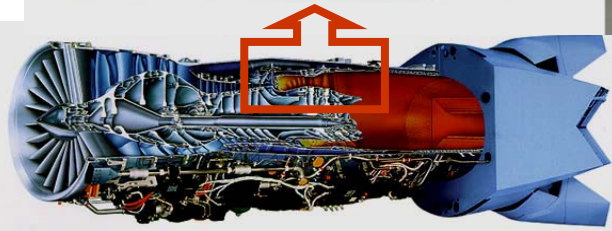
This work was supported by NASA Fundamental Aeronautics Programs

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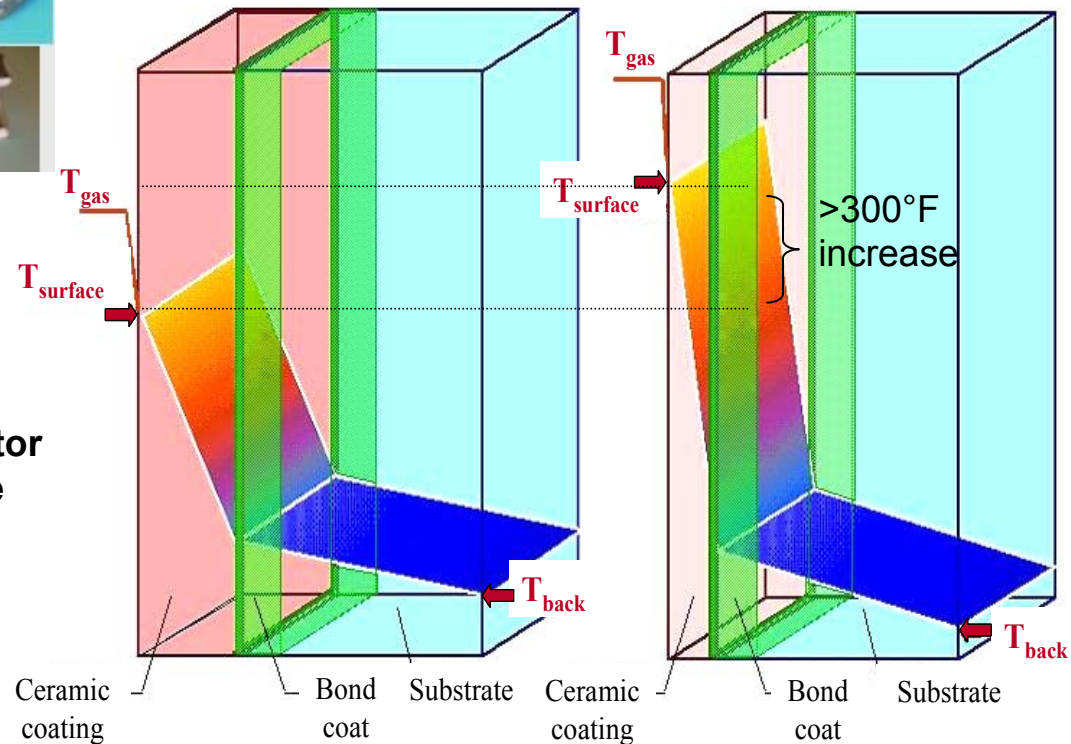
MOTIVATION

- Ceramic barrier coatings can significantly increase gas temperatures, reduce cooling requirements, improve engine fuel efficiency and reliability

Combustor Vane Blade Ceramic nozzles

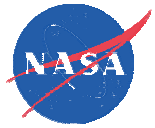


CMC combustor
liner and vane



(a) Current T/EBCs

(b) Advanced T/EBCs



Objective

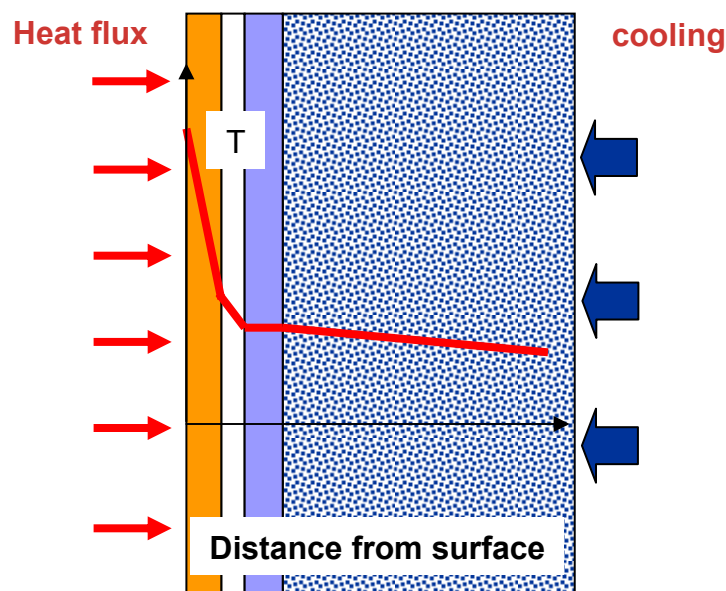
- **The coating delamination behavior under thermal gradient testing**
- **The effect of coating stability on cracking and delaminations**
- **Finite element analysis of the coating delamination driving forces**
- **Coatings design issues**
- **Summary and Conclusions**

High-Heat-Flux Tests Critical to Turbine TBC Development

— High-heat-flux laser test approach for thermal barrier coating cyclic durability

- Temperature gradient requirements: up to 200 °C/100 microns
- Heat flux requirements up to 200-300 W/cm²

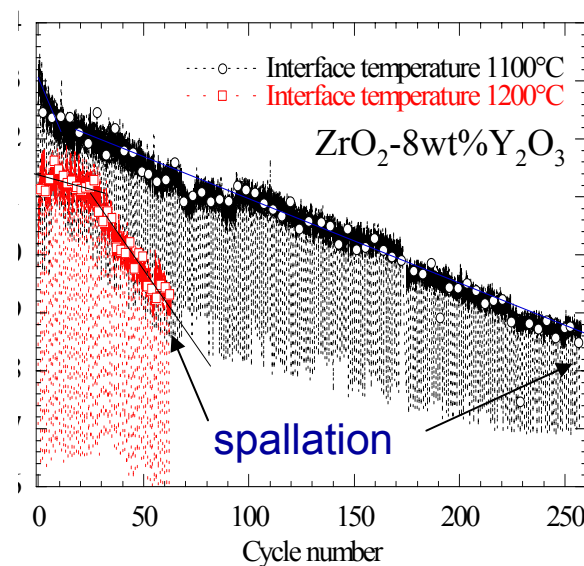
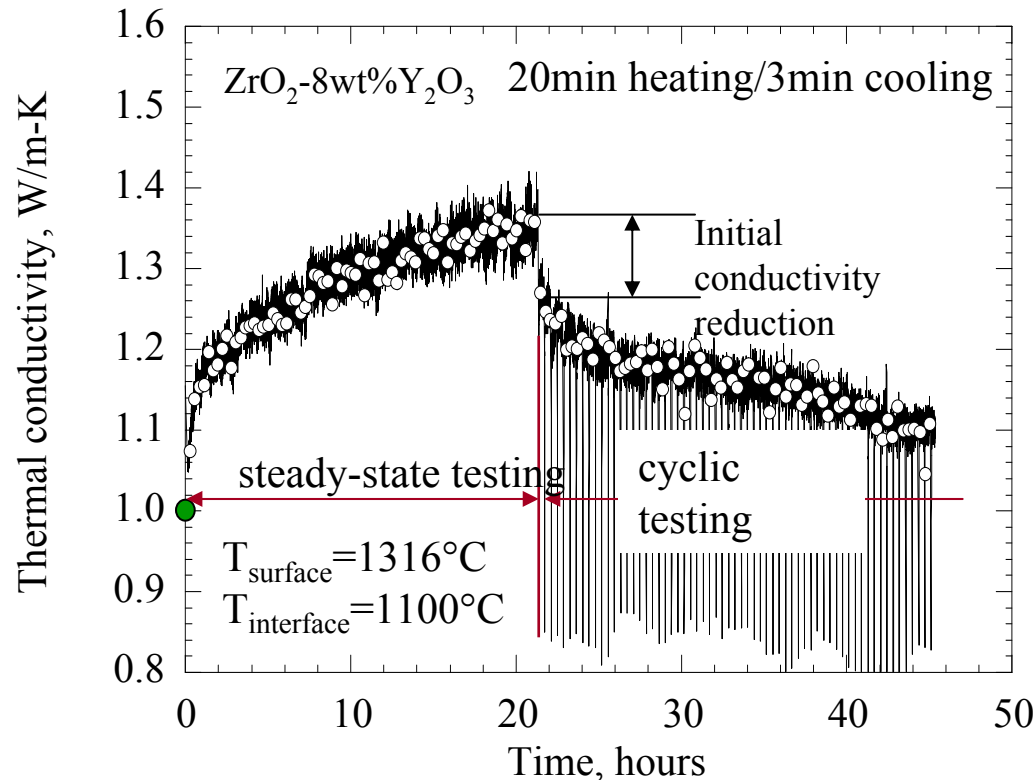
NASA CO₂ Laser Rig



Current capability up to 315 W/cm²

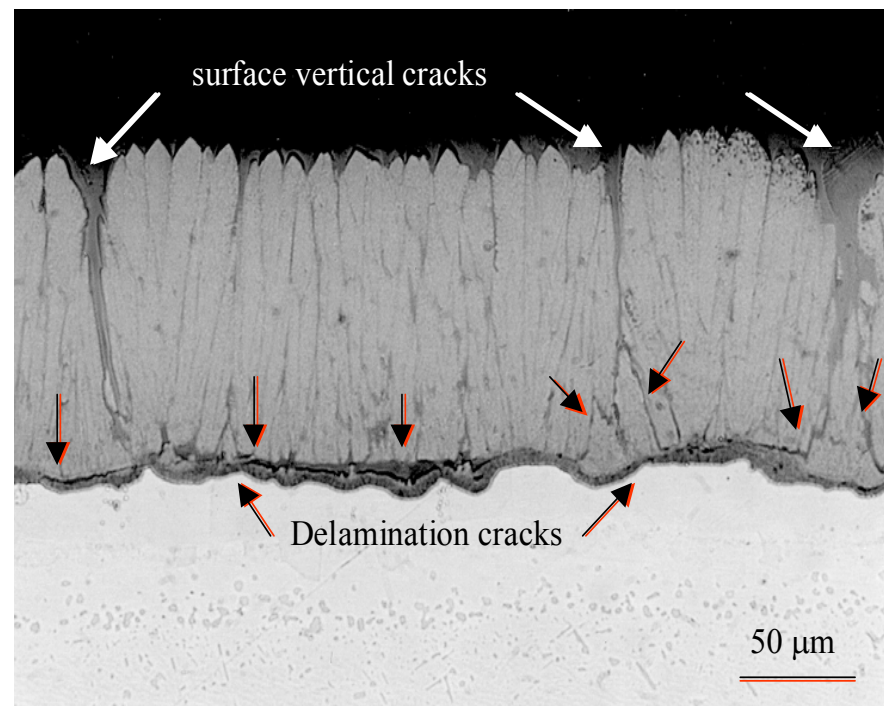
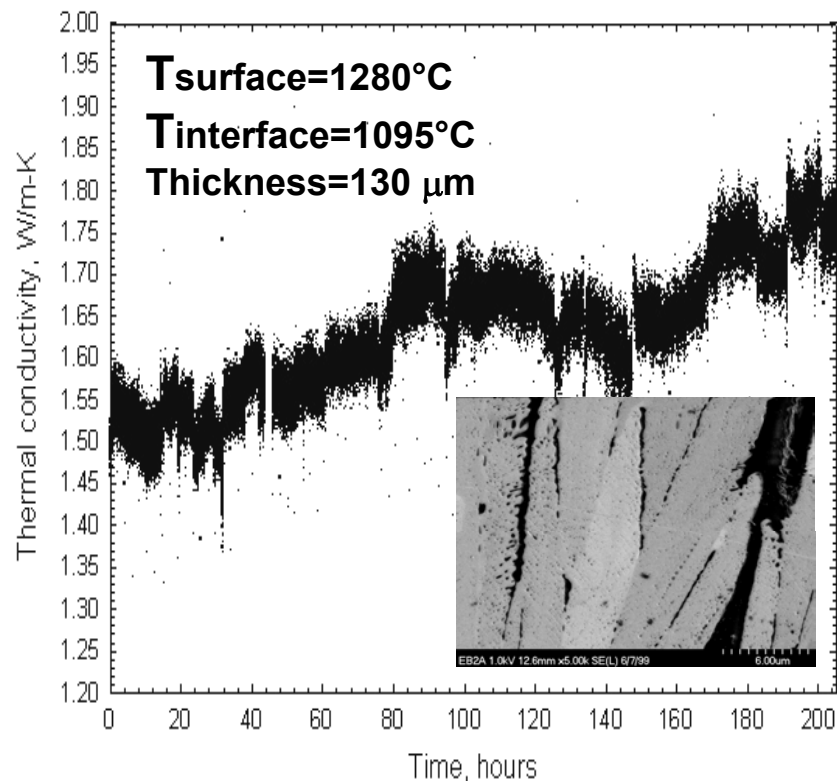
Laser Heat Flux Testing of Thermal Barrier Coatings

- Approximate constant heat flux
- Sintering induced conductivity increase during the steady-state testing
- Sintered coatings tend to have accelerated delamination under subsequent cyclic testing



High Heat-Flux Sintering Induced Cracking and Delamination in EB-PVD ZrO_2 -7wt% Y_2O_3 Coating

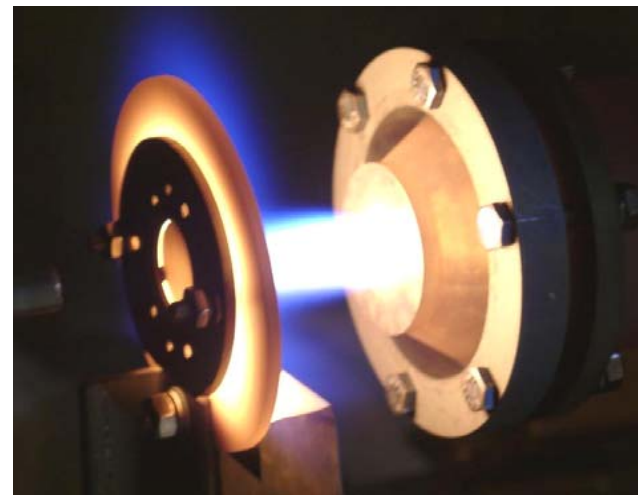
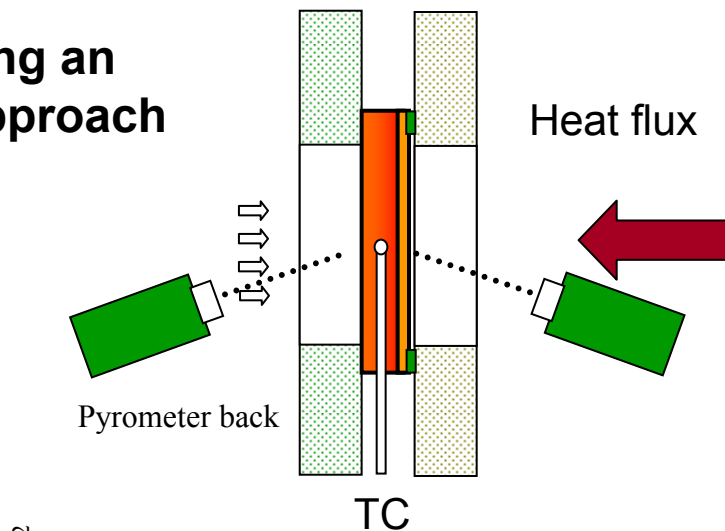
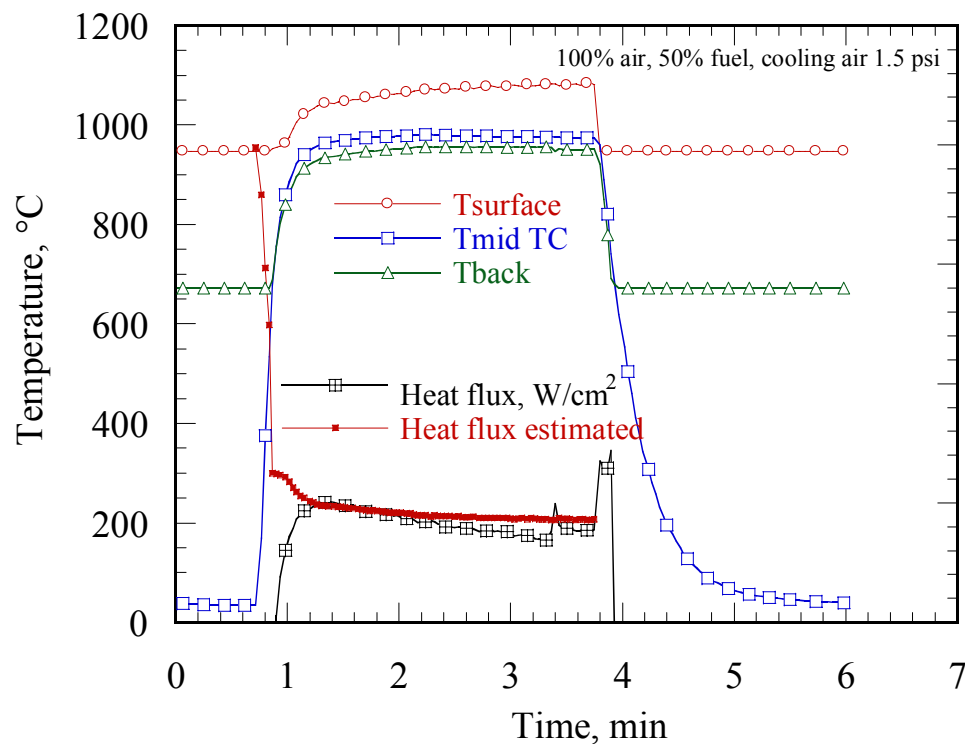
- High-heat-flux surface sintering cracking and resulting coating delaminations



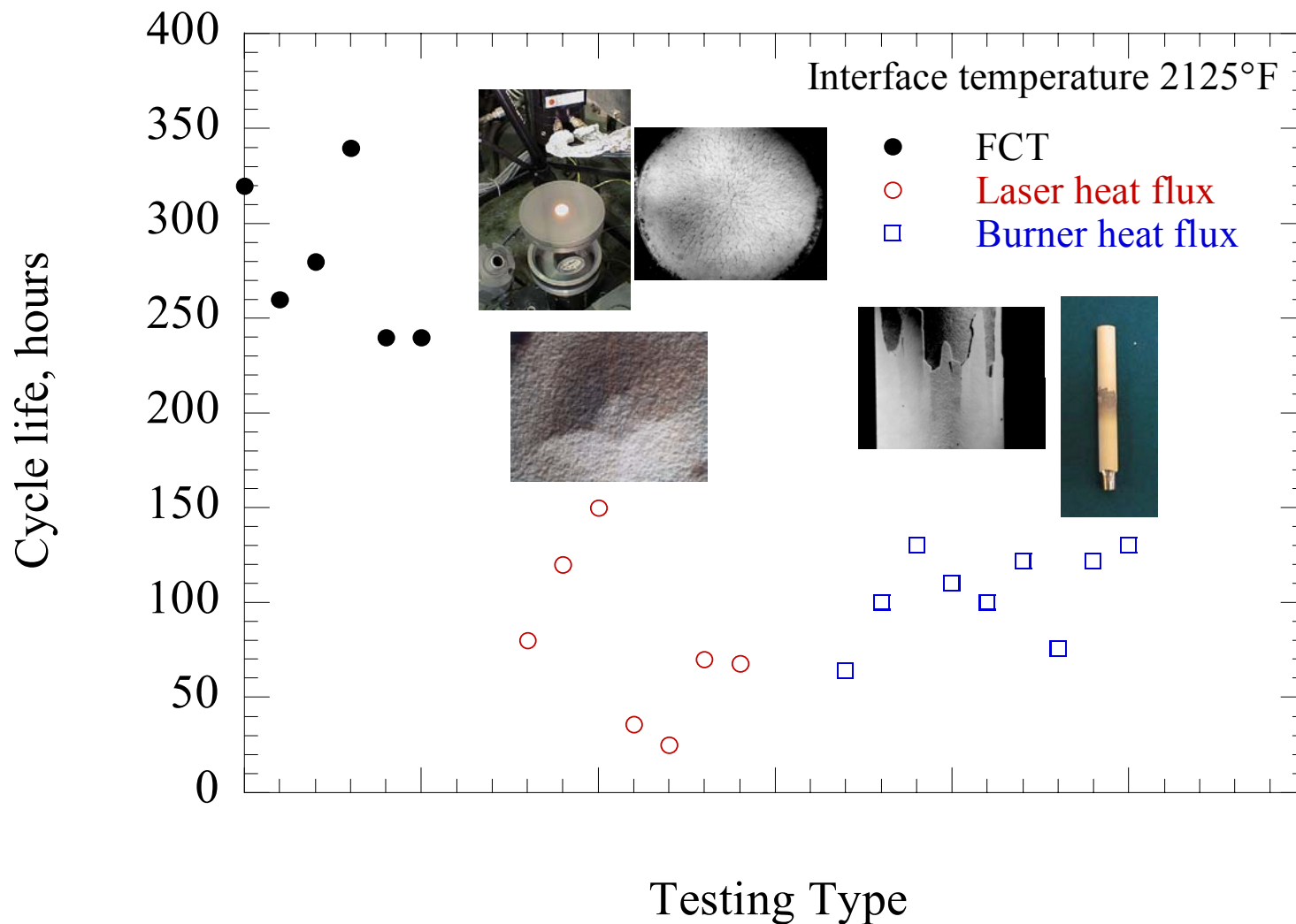
Zhu et al, Surf. Coat. Tech., Vol. 138, 2001

Burner Rig Heat Flux Characterization

- Burner rig heat fluxes characterized using an embedded thermocouple (TC) sensor approach
- Initial heat flux 100-200 W/cm² observed

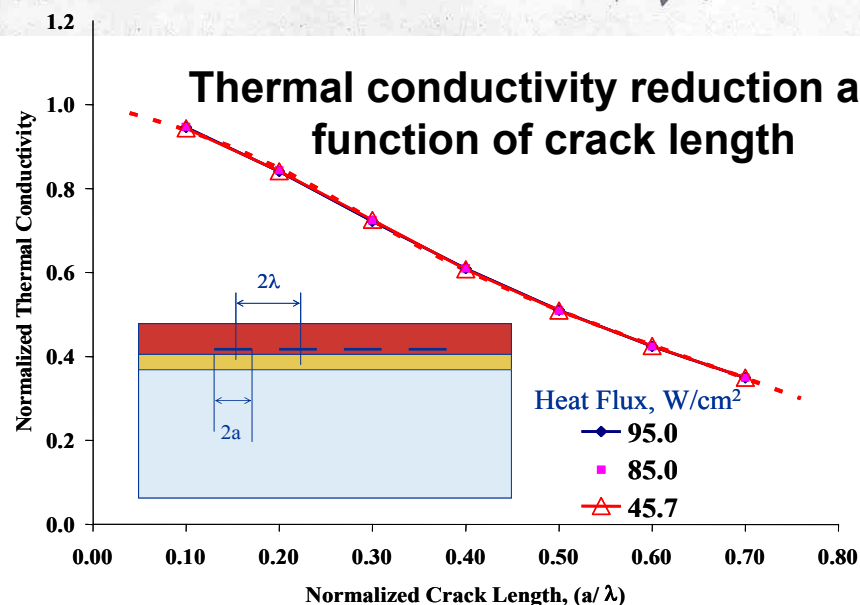
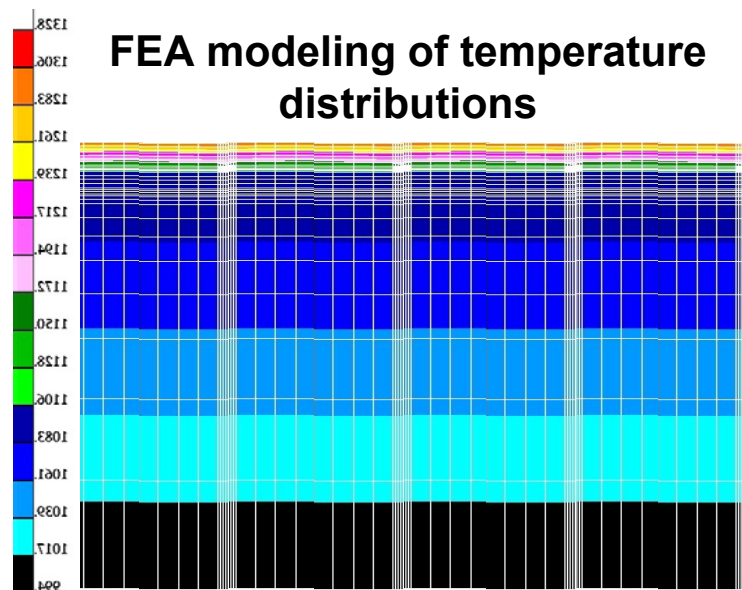
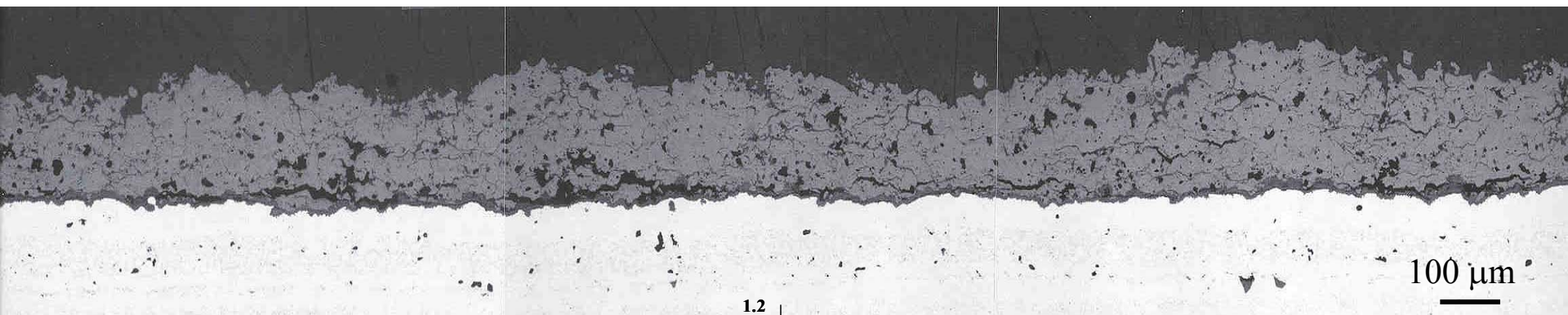


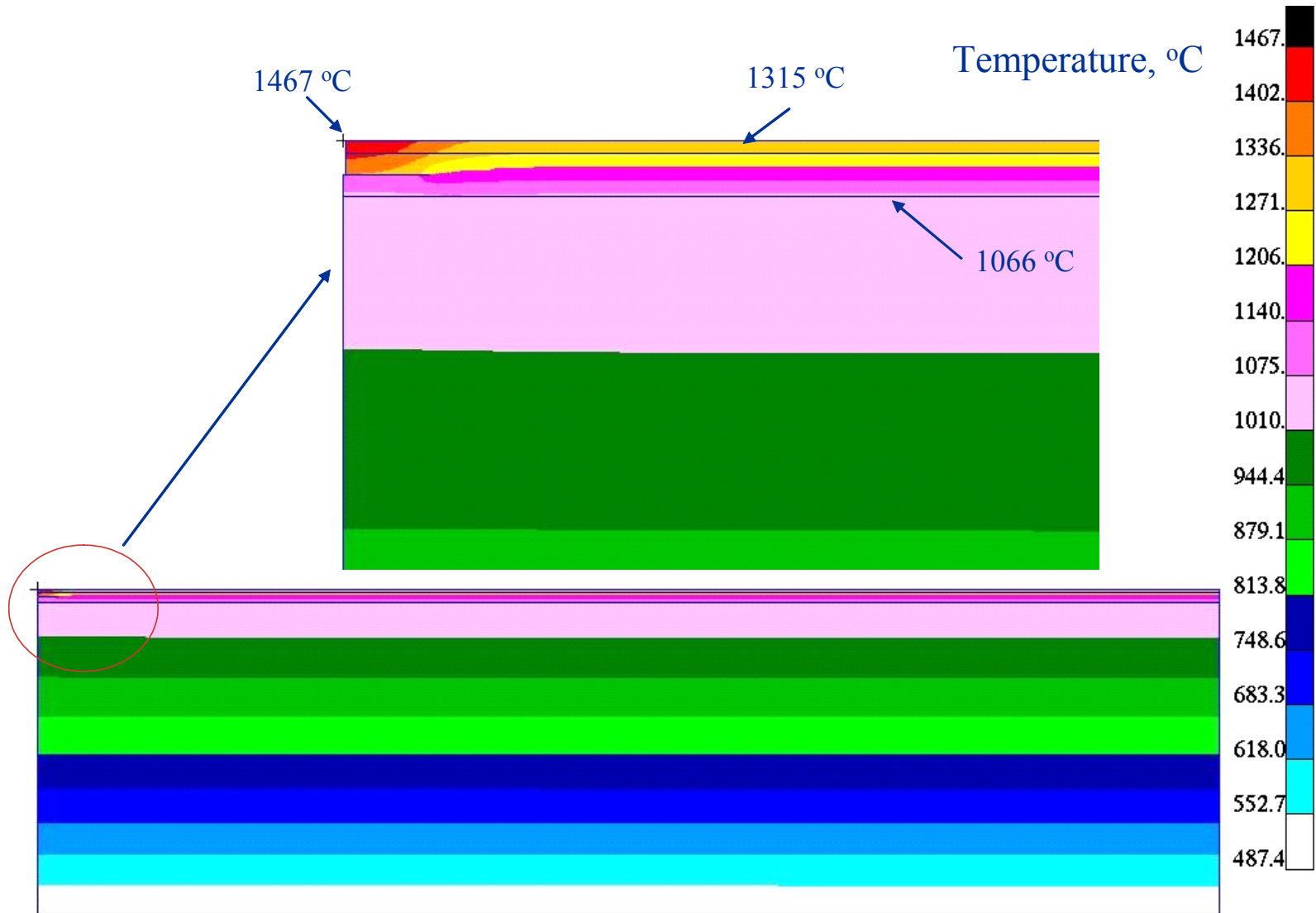
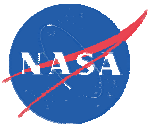
The Cyclic Life of ZrO_2 -(7-8)wt% Y_2O_3 Thermal Barrier Coatings



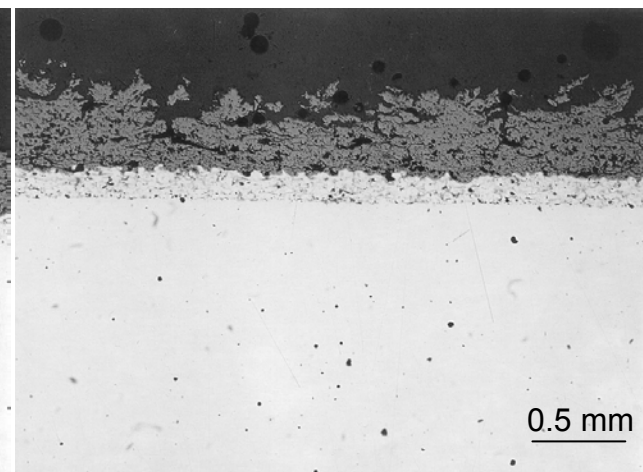
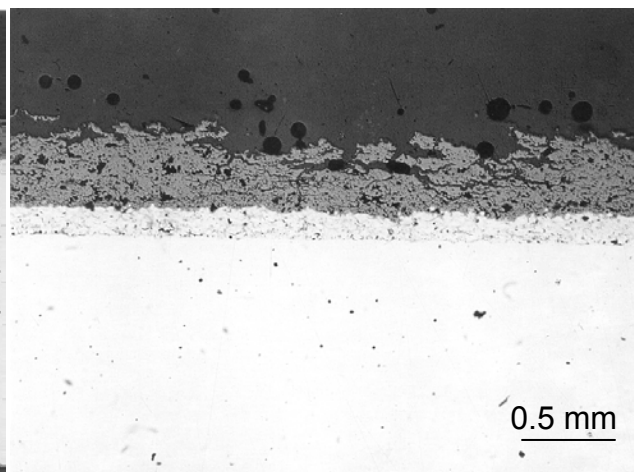
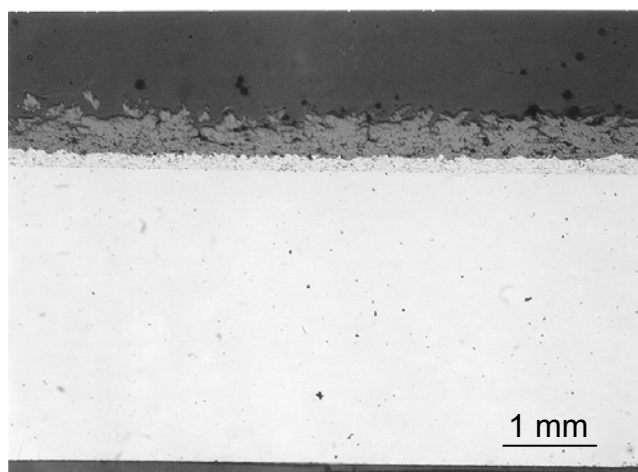
Thermal Gradient Tested TBC Delamination and Modeled TBC Delamination Induced Conductivity Reduction

- Laser tested at $T_{\text{surface}} \sim 1316^{\circ}\text{C}$ and $T_{\text{interface}} \sim 1100^{\circ}\text{C}$ under the combined steady state (22 hrs) and 20 min heating/3 min cooling cycles (256 cycles)

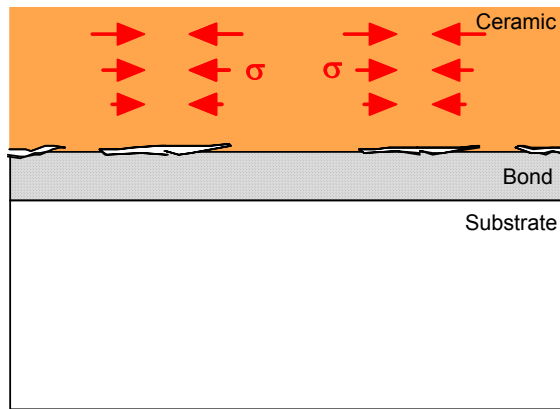




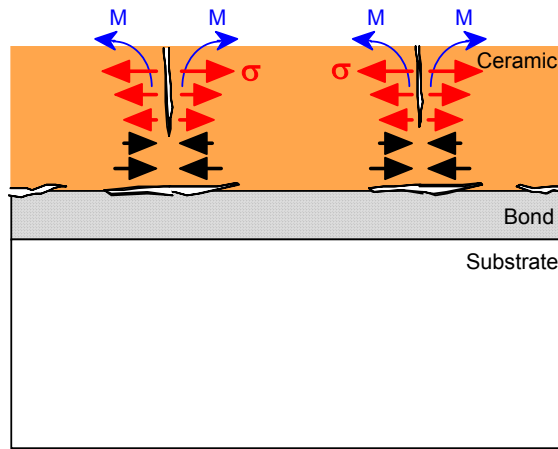
Coating Failure Modes under High Heat Fluxes and High Thermal Gradients



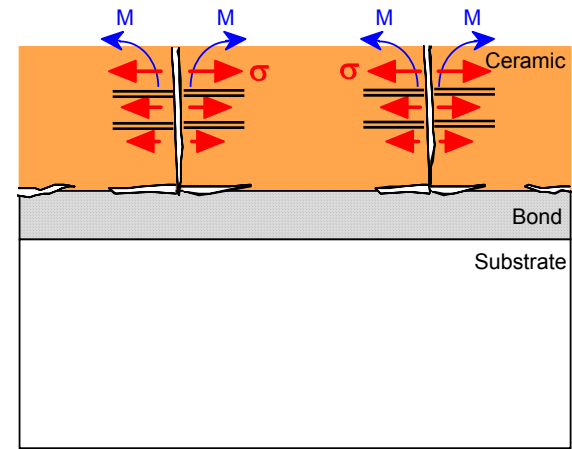
Summary of Coating Failure Modes under Thermal Gradients



(a) Low Heat Flux and High Interface Temperature

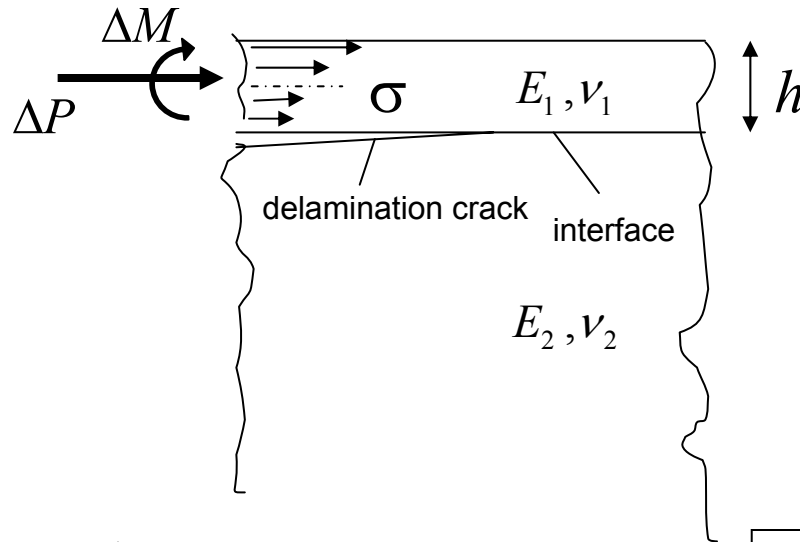


(b) Medium Heat Flux and Interface Temperature



(c) High Heat Flux and Low Interface Temperature

Delamination Driving Forces Correlated to Temperature Gradients and Modulus



$$G = \frac{1}{6} \left(\frac{1 + \nu_1}{1 - \nu_1} \right) E_1 h \left(\alpha_1 (T_s - T_0) \right)^2$$

As compared to CTE mismatch

$$G = \sigma^2 h / 2 \bar{E}$$

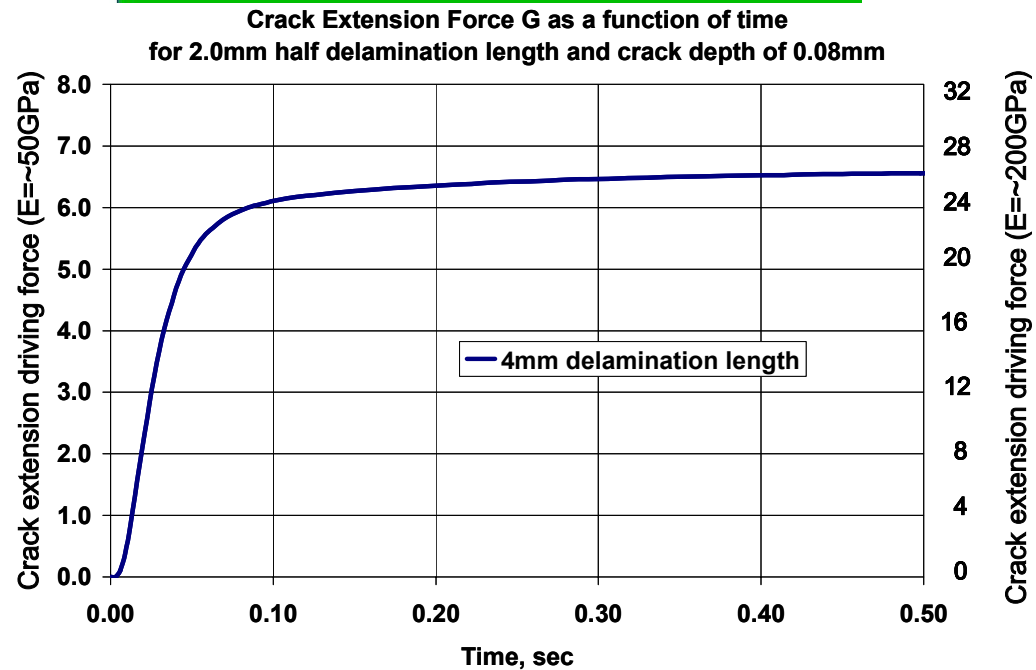
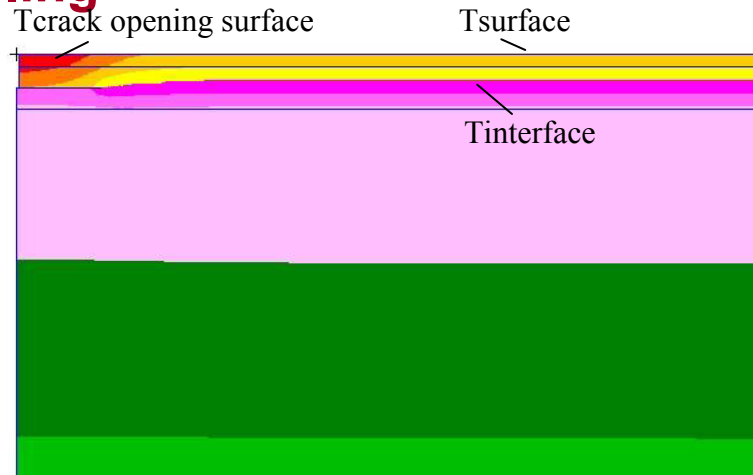
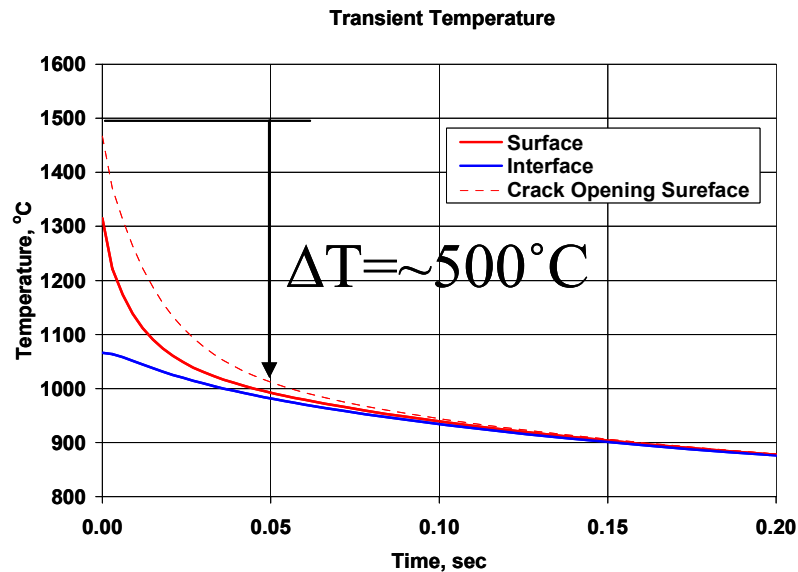
$$= [Eh(1 + \nu) / (1 - \nu)] (\Delta \alpha \Delta T)^2 / 2$$

Hutchinson, Irsee, Germany 2007;

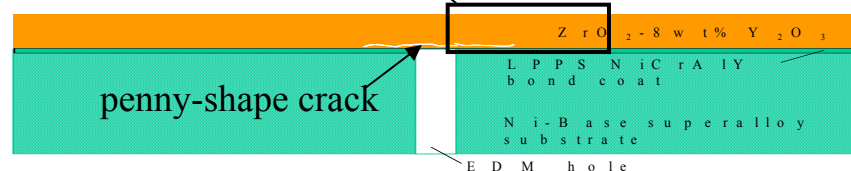
Evans and Hutchinson, Surface Coating Technology, 2007

Predicted delamination driving force G can be in the range of 20-80 J/m²

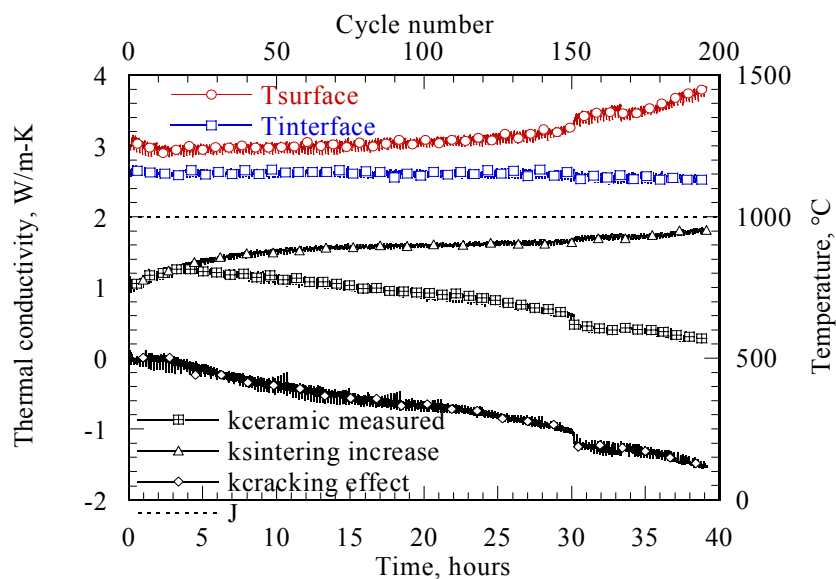
Delamination Driving Force Due to Transient Surface Cooling



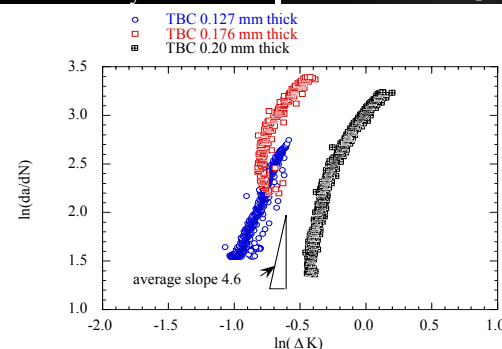
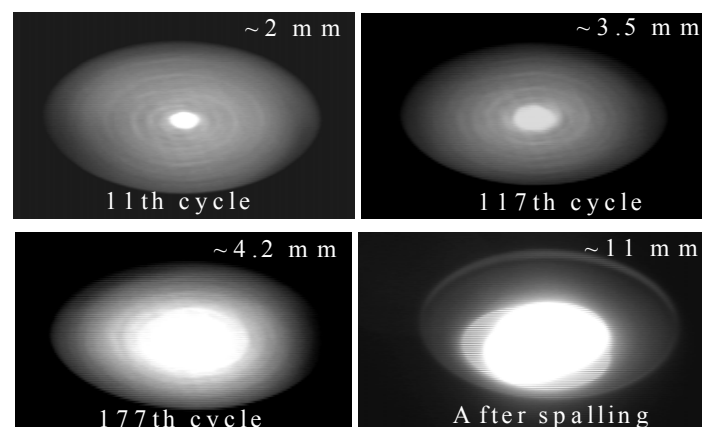
Delamination Crack Propagation observed under Heat-Flux Thermal Gradient Cyclic Condition



A center penny-shape crack propagation



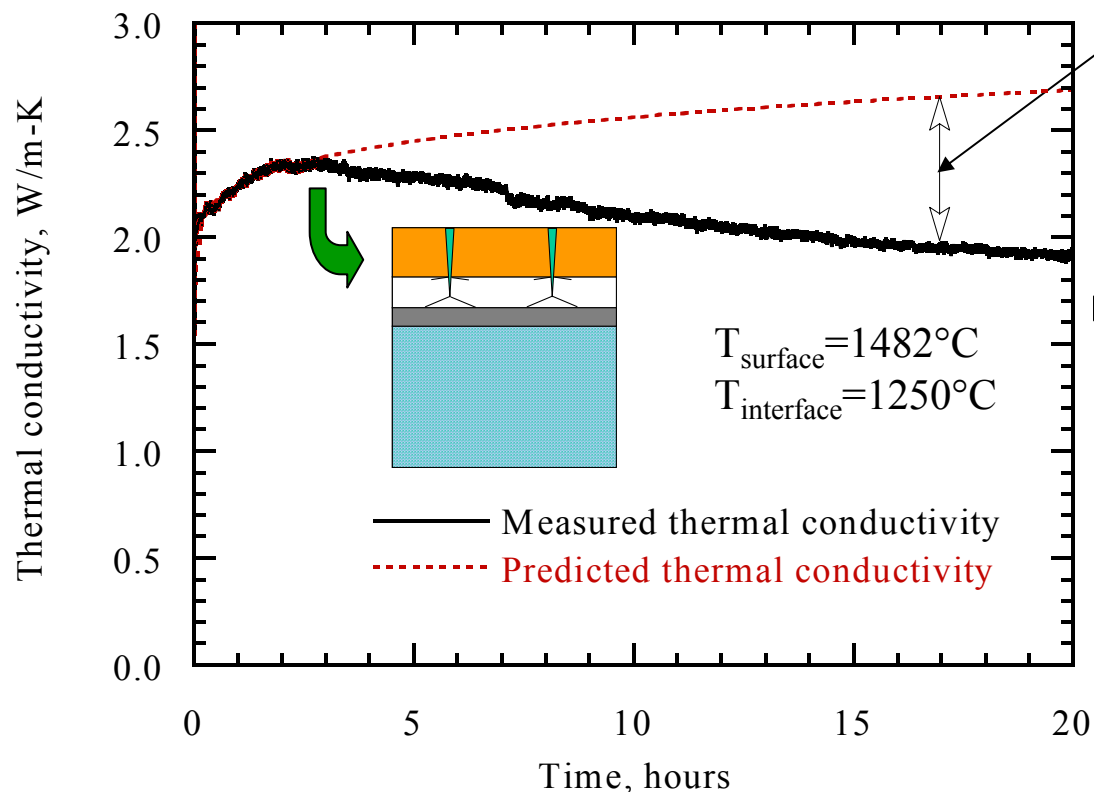
Thermal conductivity change as a function of cycle number



Crack propagation da/dN -stress intensity amplitude ΔK plot for life prediction

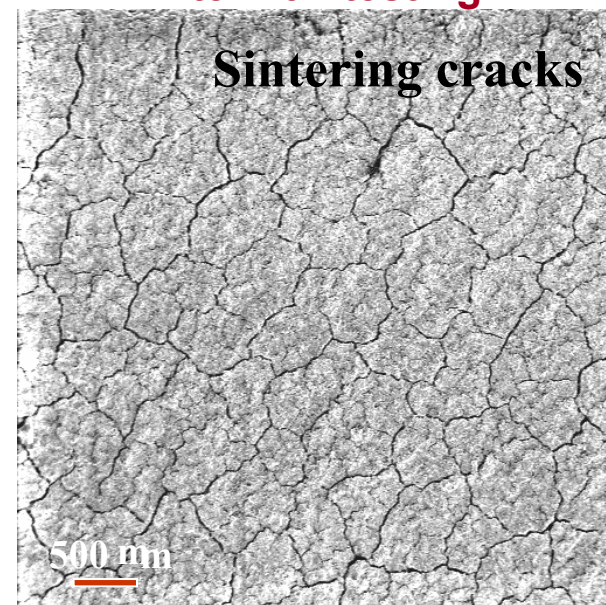
Sintering Induced Cracking in an EB-PVD ZrO_2 -7wt% Y_2O_3 Coating

- Conductivity initially increased due to sintering
- Conductivity later decreased due to coating delamination cracking resulting from the large sintering shrinkage
- * **Coating delaminates at temperature during the steady-state testing due to sintering**



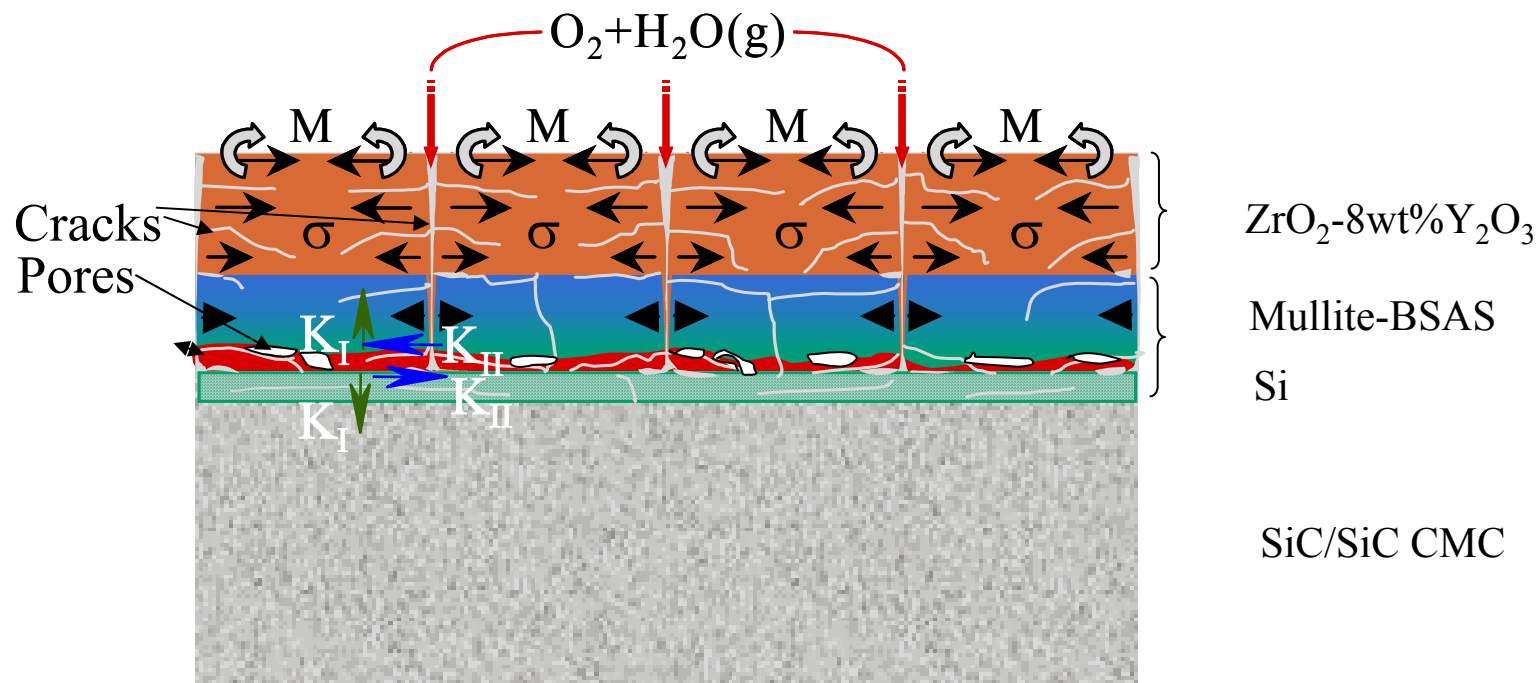
Conductivity reduction due to sintering cracking induced delamination cracking

After 20h testing



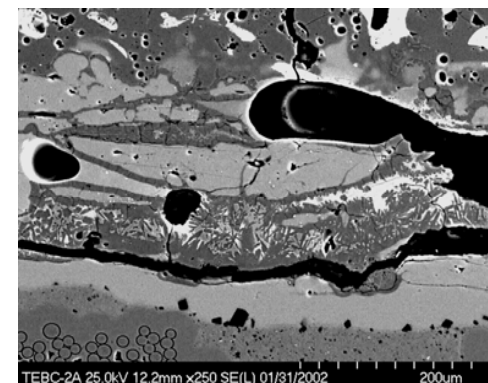
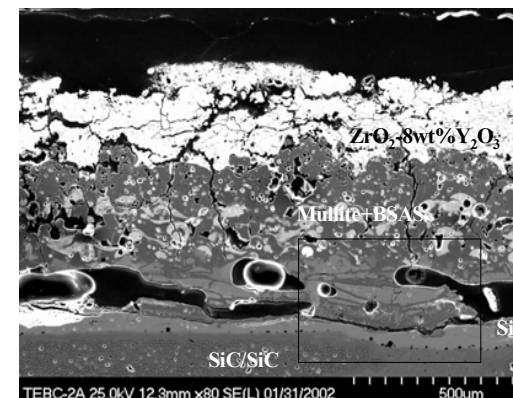
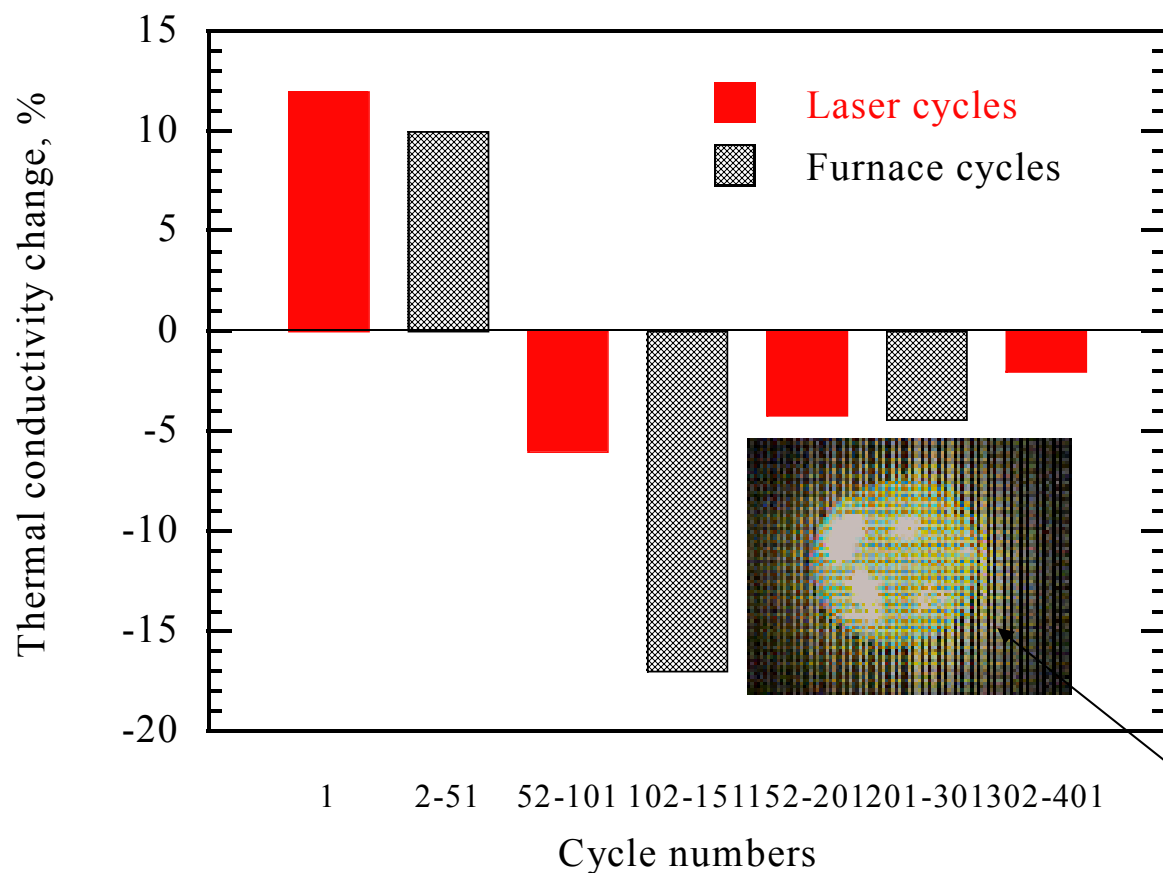
Durability Issues of Ceramic Thermal and Environmental Barrier Coating (TEBC) Systems

- Sintering and CTE mismatch induces surface wedge-shape crack propagation
- Surface cracking accelerates coating delamination under mixed mode loading (K_I and K_{II})
- Interfacial pore formation due to the chemical reactions further accelerated coating spallation under thermal gradient conditions



Accelerated Coating Degradation under Thermal Gradients

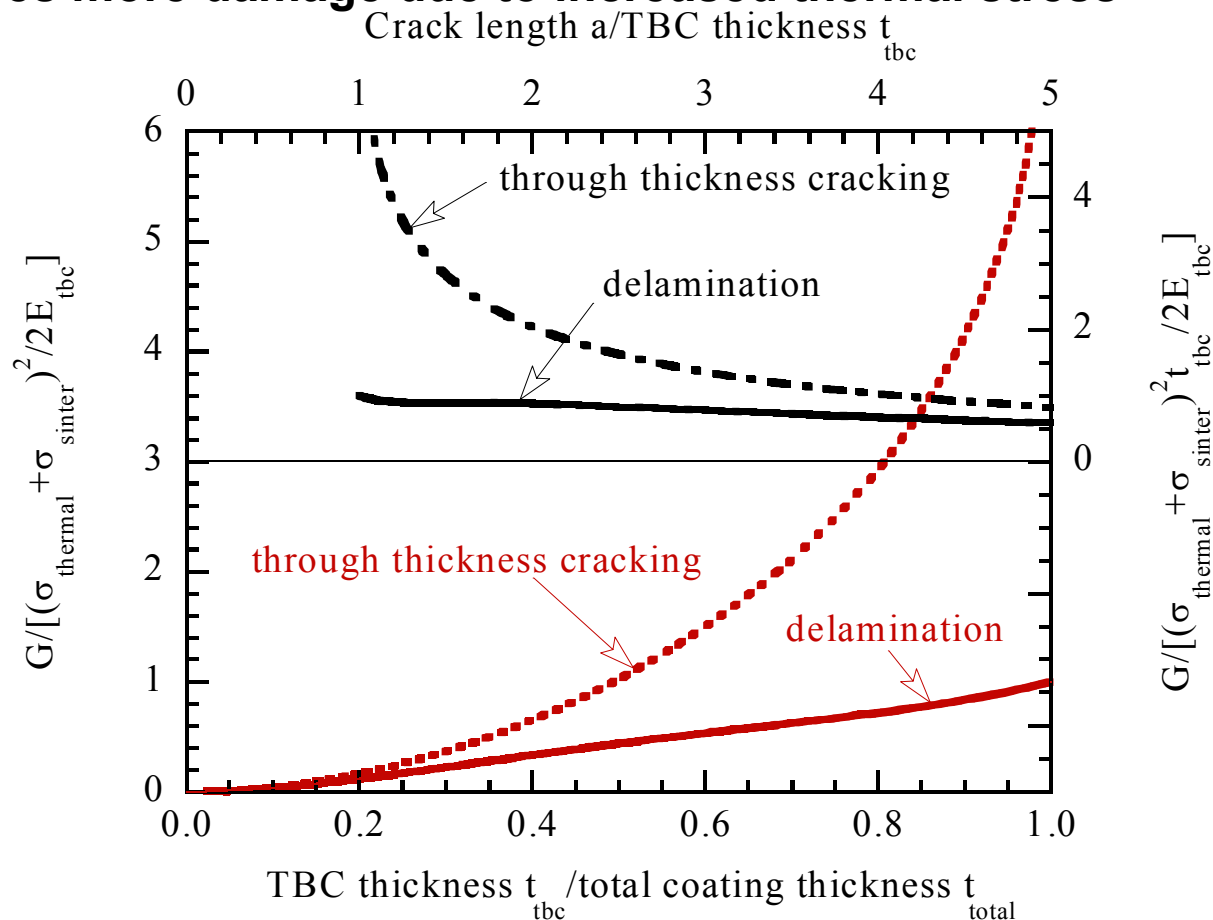
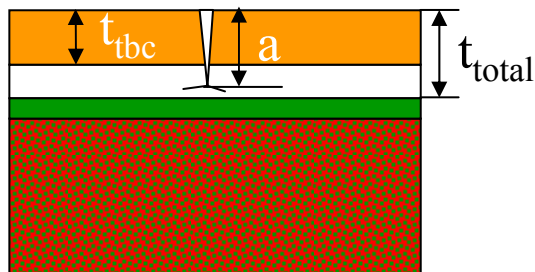
- Significant interfacial pore and eutectic phase formation due to water vapor attack and Si diffusion at the interface temperature of 1300°C under the thermal gradient cycling conditions



**Coating
spallation**

TEBC Delamination Driving Force and Design Issues

- Surface cracking and delamination are facilitated by a thicker TBC
- Low conductivity, sintering resistant, low expansion, and compliant TBCs will lower cracking driving force
- Thermal gradient imposes more damage due to increased thermal stress and sintering





Conclusions

- **The coating failure involved both time-temperature dependent sintering and cycle dependent fatigue processes**
- **Coating high temperature stability is critical durability issue**
- **Increased delamination driving force and degradation under heat flux and thermal gradient**
- **A thin, low conductivity, sintering resistant, and compliant coating will help improve coating durability**